NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 14-95

EVALUATION OF THE POSEIDON ODIN SCUBA REGULATOR FOR USE IN COLD WATER

J.R. CLARKE AND M. RAINONE

DECEMBER 1995

NAVY EXPERIMENTAL DIVING UNIT

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
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NEDU tested the breathing effort and susceptibility to freeze-up of the Poseidon Odin Jetstream SCUBA regulator. The regulator was tested in 28°F (-2°C) salt water, at depths to 198 fsw (60.7 msw). Five samples of the model were tested. The probability of regulator failure was computed from the number of cold induced incidents, and the time to failure for each incident. Under these rigorous conditions, the probability of failure for the Poseidon Odin was very low (P_f = 0.074). There were also no high breathing pressure incidents during the resistive effort measurements with a 1500 psi supply pressure, even at RMVs up to 90 L/min. The Poseidon Odin is recommended for use in sea water at 28°F and depths to 190 fsw.

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CONTENTS

ILLUSTRATIONS

GLOSSARY

ANU	Authorized for Navy Use List (NAVSEAINST 10560.2 series)
bar	Metric Unit of pressure conveniently sized for supply pressures. One bar = 100 kPa, or 14.5 psi.
cmH_2O	A metric expression of static pressure head. One cmH_2O = 0.01 meters of pure water. In pressure equivalents, 1 cmH_2O= 0.736 torr, 981.8 Pa, or .0982 kPa.
flow resistance	A mechanical impedance describing the proportionality between driving pressure and the resulting flow. Units are $cmH_2O \cdot L^{-1} \cdot sec$ or $kPa \cdot L^{-1} \cdot sec$. The average resistance over a tidal breath can be derived from $\overline{P}_V$ and RMV.
fsw	Feet of Seawater, a unit of pressure. One fsw = 0.3063 msw.
J/L	Joules per liter, unit of measure for "Work of Breathing" normalized for tidal volume. One J/L = 1 kPa.
kPa	Kilopascals or newton/m^2, unit of pressure. One kPa ~ 10.2 cmH_2O
msw	Meters of Sea Water. One msw = 3.2646 fsw.
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
psi	Pounds per Square Inch, an English measure of pressure. One psi = 6.895 kPa. 1 bar = 14.504 psi.
$\overline{P}_V$	Volume averaged pressure, or resistive effort, otherwise known by the misnomer Work of Breathing (WOB). A computer derived estimate of total resistive respiratory effort obtained when breathing a regulator with a mechanical breathing simulator.
resistance	see flow resistance
RMV	Respiratory Minute Volume with units of $L \cdot min^{-1}$

INTRODUCTION

The U.S. Navy has a requirement to identify open circuit SCUBA regulators which perform reliably in 28°F (-2°C) water and depths down to 190 fsw (58.2 msw). To this end, NEDU was tasked[1] to test and evaluate production models of commercially available, open circuit SCUBA regulators to determine those which best meet the U.S. Navy's requirement. This is a report on the Poseidon Odin regulator.

Poseidon Industri ab. (Västra Frölunda, Sweden) provided five samples of the Odin Jetstream (model 3960) for evaluation. The first stage is a diaphragm-actuated, balanced regulator with shear venturi boost reducing valve, which reduces the primary pressure (cylinder pressure) to approximately 145 psi. The reduced pressure (secondary pressure) is then applied to the second stage regulator.

According to Poseidon, when diving in water below 43° F (6° C) the outer spring housing of the first stage should be provided with an anti-freeze cap to prevent direct contact with the water. This is necessary because of the considerable cooling that takes place when air from the high pressure chamber expands in the intermediate pressure chamber. This cooling can otherwise cause ice formation around the diaphragm balance spring, and thereby prevent the spring and diaphragm from functioning.

The second stage regulator is an upstream diaphragm-actuated, servo assisted regulator with safety relief and a fixed ejector system. It contains a purge button and sensitivity switch for added control of breathing effort.

For regulators designed for use in relatively warm water (>37°F), the primary criterion by which the regulators are judged during unmanned testing is their ability to meet the Performance Goal Standards[2] for volume-averaged pressure ($\overline{P}_V$) or resistive effort. For diving under polar ice, however, a more important consideration than breathing effort is resistance to freeze-up. In modern regulators, freeze-up is usually manifested as free-flow due to either a second stage failure, or first stage loss of intermediate pressure control. On rare occasions the first stage can fail with complete blockage of gas flow. Since freeze-up is a potentially life-threatening occurrence, we placed primary emphasis on regulator freeze-up susceptibility, with secondary emphasis on $\overline{P}_V$.

METHODS

Regulators

The five regulators supplied to NEDU by Poseidon were 1995 models, with serial numbers 3960401992 to 3960401996. They were set up according to Poseidon instructions and bench tested prior to the initial cold water exposures.

Environmental Control

The test regulators were submerged in brine-filled tanks with water temperature maintained at 28°F to 31°F (-2.2°C ± -0.5°C). The brine mixture was prepared with tap water and Instant Ocean® salt mixture (Aquarium Systems, Mentor, OH). The salinity of the brine solution was approximately 45 parts per thousand to prevent ice formation on the heat exchanger coils and loss of temperature control. Salinity was measured by the refractive index of the brine using an automatic temperature compensated hand refractometer (Model 10419, Reichert Scientific Instruments, Buffalo, NY). The water content in the high pressure air supply was measured by a phosphorous pentoxide (P_2O_5) detector system, and was found to be 23 ppm, translating to a -65.5°F dew point.

"Exhaled" air from the breathing machine was heated and humidified such that the gas temperature measured at the chrome tee (connected to the mouthpiece of the second stage regulator) ranged between 10° and 20°C. Under steady-state conditions, the exhaled temperature (T_{ex}) varied with depth, tending to be higher at the greater depths.

Breathing Simulator

A computer controlled electro-mechanical breathing simulator (Battelle, Columbus, OH) ventilated each regulator at respiratory minute volumes (RMV) ranging from 22.5 to 90 $L \cdot min^{-1}$, thus emulating varied diver work rates. Supply pressure to the first stage was maintained at 1500 psi (103.4 bar) for one set of tests, then reduced to 500 psi (34.5 bar) for another set. This procedure was in accordance with NEDU Test Plan 93-21, except that in this instance the regulators were warmed and dried before repeating the cold water exposure with 500 psi supply pressure[3]. Recordings of pressure-volume loops were taken at 33 fsw (10 msw) increments. Test depths ranged from 0 to 198 fsw (0 to 60.7 msw). Testing at a specific RMV/depth parameter was terminated if inhalation or exhalation pressure exceeded 4 kPa, the working limits of the pressure transducers currently used in the Experimental Diving Facility.

Statistics

Descriptive statistics were used to obtain the mean and standard deviation of the resistive effort data. The one-sided, one sample T-test was used to compare test results with the NEDU performance goal for SCUBA regulators. Examples of the application of this test is described in Chapter 7 of the NEDU Technical Manual on Unmanned Test Methods and Performance Goals[2]. Statistical significance was established at $P < 0.05$.

Freeze-Up Dive Profiles

NEDU routinely uses a fixed depth, worst case protocol for evaluating freeze-up susceptibility. This consists of diving the regulator to 198 fsw (60.7 msw) and breathing it at an

RMV of 62.5 $L \cdot min^{-1}$ for 30 minutes. This run is repeated at 132 fsw (40.4 msw) and 33 fsw (10.1 msw).

Failure Probability Determination

For freeze-up susceptibility tests, both the number of regulators freezing and the time at which they froze was considered. Those results were empirically combined in the following manner.

$$P_f = \sum_{i=1}^{n} \left(\frac{n^{-1} \cdot E_i}{t_i^k}\right) \qquad (1)$$

where P_f is the probability of failure (ranging between 0 and 1), n is the number of regulators, E is a binary event equal to 0 if there is no failure and 1 if the regulator fails, t is the time to failure in minutes, and k is an empirical constant = 0.3, chosen to provide reasonable probabilities. By NEDU convention, n = 5. If all 5 regulators freeze after 1 minute, then

$$P_f = \left(\frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}}\right) = 1.0$$

If no regulators fail, then $P_f = 0$. If 2 freeze, one at 18 minutes and one at 28 minutes, then $P_f = 0.158$. When ranking the desirability of various cold water regulators, a regulator with a P_f of 0.158 would be preferred over one with a P_f of 0.34.

$$P_f = \left(0 + 0 + 0 + \frac{0.2 \cdot 1}{18^{0.3}} + \frac{0.2 \cdot 1}{28^{0.3}}\right) = 0.158$$

The above empirical probability estimation is nothing more than a way of quantitatively comparing, or of ranking, various regulators. It does not estimate the actual probability of freeze-ups during an open water dive. That probability is dependent upon the duration of the dive relative to the expected time of regulator freeze-up.

Resistive Effort

$\overline{P}_V$ levels are a computer derived estimate of total respiratory effort obtained when breathing a regulator with a mechanical breathing simulator, measured in kPa (or in more cumbersome terms, joules per liter, J/L). $\overline{P}_V$ averages were derived from the mean of tests on up to five individual regulators for each model.

Average Resistance

The average resistance per breath is found by the following equation[4]:

$$R = \frac{2 \cdot \overline{P}_V}{\pi^2 \cdot RMV}$$

RESULTS

Freeze-up Susceptibility

Four Odin regulators completed the entire thirty minute susceptibility test with no difficulty. One regulator began free-flowing after 28 min. From Equation (1) the P_f for the Poseidon Odin regulators was 0.074.

Resistive Effort Determination

The mean resistive efforts for the Odin regulator at 1500 psi (103.4 bar) and 500 psi (34.5 bar) supply pressure are shown in Figure 1. The horizontal lines in each panel represent the NEDU performance goal[2] for SCUBA regulators, 1.37 kPa. A few runs at the low supply pressure were aborted by the operators to protect the test instrumentation whenever the inhalation or exhalation pressures exceeded 4 kPa. The plotted means represent the average for all runs that were completed by all 5 regulators. Typically, the $\overline{P}_V$ of greatest interest is that at an RMV of 62.5 $L \cdot min^{-1}$ (upward pointing triangles) at the deepest depth.

The $\overline{P}_V$ at an RMV of 62.5 L/min significantly exceeded NEDU performance goals for SCUBA regulators at depths of 99 fsw and deeper with a supply pressure of 1500 psi. This is not an unexpected result for regulators being used in frigid water. Surprisingly, at a supply pressure of 500 psi, the regulator met the performance goals through 165 fsw. We can only speculate that the adiabatic cooling associated with a first stage pressure drop from 1500 psi to 145 psi may have hindered first stage performance compared to the pressure drop from 500 to 145 psi.

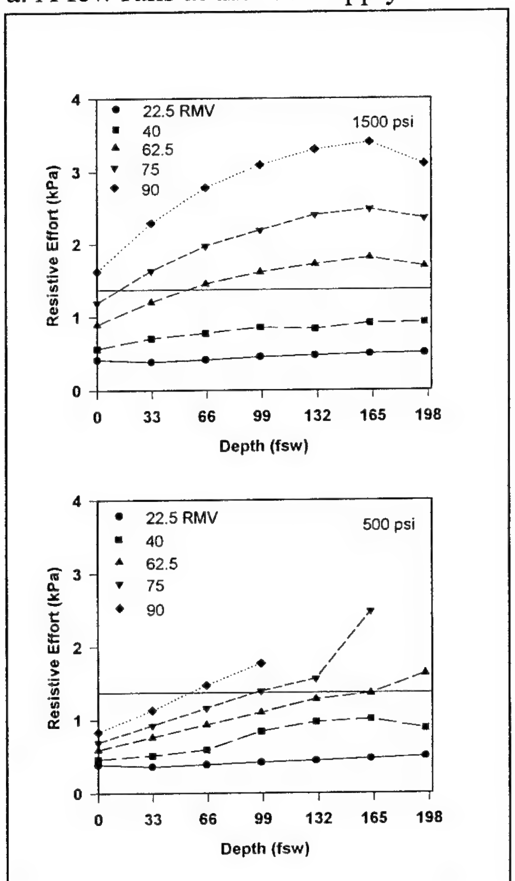

Figure 1. Resistive effort at moderate (top panel) and low supply pressures.

Event Incidence in Resistive Effort Tests

The primary purpose of resistive effort measurements was to describe the breathing effort of the regulators. However, two events could hamper those measurements; one is excessively high

ventilatory pressures, and the other is regulator free flow. The two events are considered of equal importance since both could be due to the effects of cold water.

Figure 2 is a plot of the dependent variable, event incidence with a 1500 psi (103.4 bar) supply pressure, against the independent variables mass flow rate and test sequence. The independent variables are located on the horizontal plane. The test sequence represents the order in which tests were conducted on each regulator. Each test began at 190 fsw with an RMV of 22.5 L·min^{-1}. RMVs were increased sequentially through 90 L·min^{-1}, and then the chamber was brought up to the next shallower depth before the RMVs were repeated. Consequently, tests at the surface and 90 L·min^{-1} were the last runs conducted. For both regulators, the entire test sequence took between 1 hr and 1 hr 15 min. Therefore, each sequence number represents an interval of about 2 min.

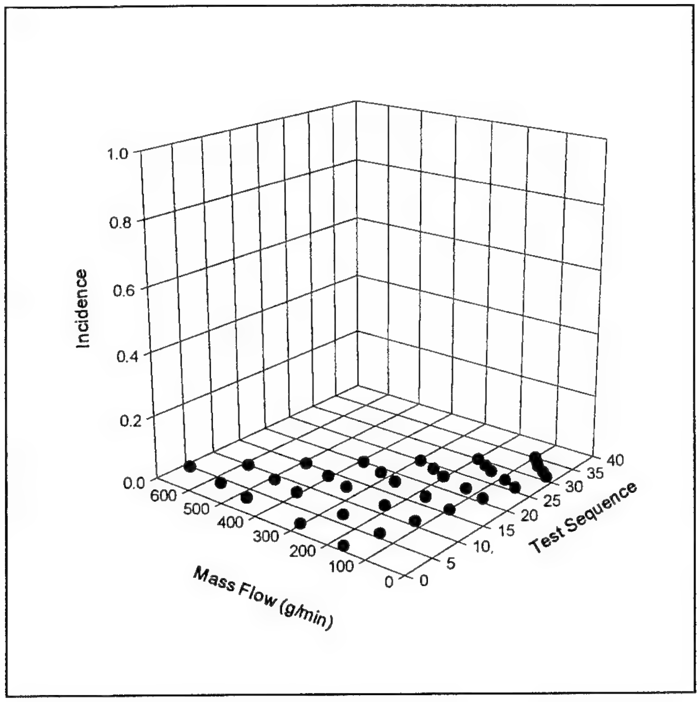

Figure 2. Incidence of high pressure events during resistive effort at 1500 psi supply pressure.

Mass flow, with units of grams per min (g/min), is shown on the second horizontal axis. Mass flow is defined as:

$$\dot{M} = \rho \cdot RMV \cdot \frac{P_{amb}}{P_0}$$

where ρ is gas density in g/L at 1 atm absolute and 0° C, RMV is ventilation in L·min^{-1}, and P_{amb} is ambient pressure in absolute units. P_0 is the absolute pressure at 1 atm, a factor required to generate a dimensionless pressure ratio. Mass flow rate reflects the mass of gas flowing through the regulator each minute.

<u>Breathing Resistance</u>

Average resistance as a function of depth (top panel) and RMV (bottom panel) are shown for the Odin Jetstream at a supply pressure of 1500 psi (Figure 3) and 500 psi (Figure 4). There are currently no standards or performance goals for regulator resistance.

Each data point represents the mean resistance of 5 regulators. When plotted against RMV, the average resistance drops at shallow depths, presumably due to the inspiratory assistance

contributed by the second-stage venturi. Figure 5 compares the Odin's resistance with that of a fixed orifice. At deep depths, the regulator seems to loose the benefit of the venturi, and assumes the resistive characteristics of an orifice.

The average resistances remained below 5 $cmH_2O \cdot L \cdot sec^{-1}$ under all conditions, and were below 4 $cmH_2O \cdot L \cdot sec^{-1}$ at an RMV of 62.5 $L \cdot min^{-1}$. To put these numbers into perspective, fifty years ago Silverman et al[5] specified that breathing apparatus used at high ventilatory rates at the surface should have an inspiratory resistance no greater than 4.5 $cmH_2O \cdot L \cdot sec^{-1}$ and an expiratory resistance no higher than 2.9 $cmH_2O \cdot L \cdot sec^{-1}$ at a flow rate of 1.42 $L \cdot sec^{-1}$. The average flow rate for an RMV of 62.5 $L \cdot min^{-1}$ is 1.04 $L \cdot sec^{-1}$, therefore the average resistance of the Odin at an RMV of 62.5 $L \cdot min^{-1}$ and the deepest depth does not depart greatly from Silverman's resistance goals for equipment to be used at the surface. We consider this to be an excellent result for cold water regulators.

DISCUSSION

The Poseidon Odin regulator performed well during a freeze-up susceptibility test that is admittedly far more severe than would probably be seen in actual diving. Therefore, NEDU can confidently recommend this regulator for cold water diving.

Even though the resistive effort studies primarily examine breathing resistance, they have induced free flow due to freeze-up in other regulators. For that reason, NEDU uses three dimensional plots such as Figure 2 as an adjunct to the standard freeze-up evaluation. In this case, the flat, featureless nature of the graph shows that the performance of the Odin was virtually flawless.

The problem with using the resistive effort studies as the only freeze-up evaluation is that flow is intermittent during those tests. The breathing machine is stopped for 30 sec to a minute between each test sequence. It is not known how this periodicity might affect the freeze-up probability. On the other hand, taken at face value, the current results suggest that no work rate limitation need be placed on the regulator down to 190 fsw in 28° F water.

Venturi Action

Figure 5 shows that flow resistance averaged over a breath begins to rise in the fashion of an orifice at ambient pressures of 6 atm absolute or more. We can speculate that the suction created by a second stage venturi is more pronounced at shallow depths than at deeper depths. The Poseidon Odin intermediate pressure was 145 psi above ambient. At 165 fsw, ambient pressure is 88.2 psi absolute. Therefore, intermediate pressure was 145 + 88.2 psi or 233 psi. The expansion of gas across the second stage orifice is therefore affected by a pressure drop from 233 psi to 88 psi, resulting in a 2.6 times expansion at 165 fsw. At the surface, the expansion ratio would be (145 + 14.7 psi) / 14.7 psi or 10.9. Therefore, gas expansion is about four times greater near the

surface than at depth. To the extent that venturi action is controlled by volume expansion, we would expect the induced venturi to be more vigorous at shallow depths than at deeper depths.

RECOMMENDATION

On the basis of the above tests, the Poseidon Odin regulator is recommended to be authorized for Navy use (ANU) in water temperatures as cold as 28°F to a maximum depth of 190 fsw.

No SCUBA regulator can completely eliminate the risk of freeze-up. Tests on regulators more prone to freezing than the Odin have shown that depth, time, and flow rate are all risk factors. Consequently the safest dives will be shallow, short duration, low work rate dives. The more extreme the dive conditions, the greater the risk of a freeze-up incident. In the Poseidon Odin, however, that risk seems very small.

REFERENCES

1. Naval Sea Systems Command, *Commercial Diving Equipment Test and Evaluation,* Task 95-10, 1 Jan 95.

2. Navy Experimental Diving Unit, *U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus*, TECH MAN 01-94, June 1994.

3. *Evaluation of Commercial Open Circuit Scuba Regulators (Unmanned/Manned).* NEDU TP 93-21 (Limited Distribution), Navy Experimental Diving Unit, May 1993.

4. Clarke, J. *Measurement of Average Resistance In Underwater Breathing Apparatus*. Energy Week '96 Conference Proceedings, ASME, In Press.

5. Silverman, L., G. Lee, T. Plotkin, L. Amory, and A.R. Yancey. *Fundamental factors in the design of protective respiratory equipment. Inspiratory and expiratory air flow measurements on human subjects with and without resistance at safe work rates.* Report 5732, USAAF Office Sci. Res. Develop., Aug., 1945.

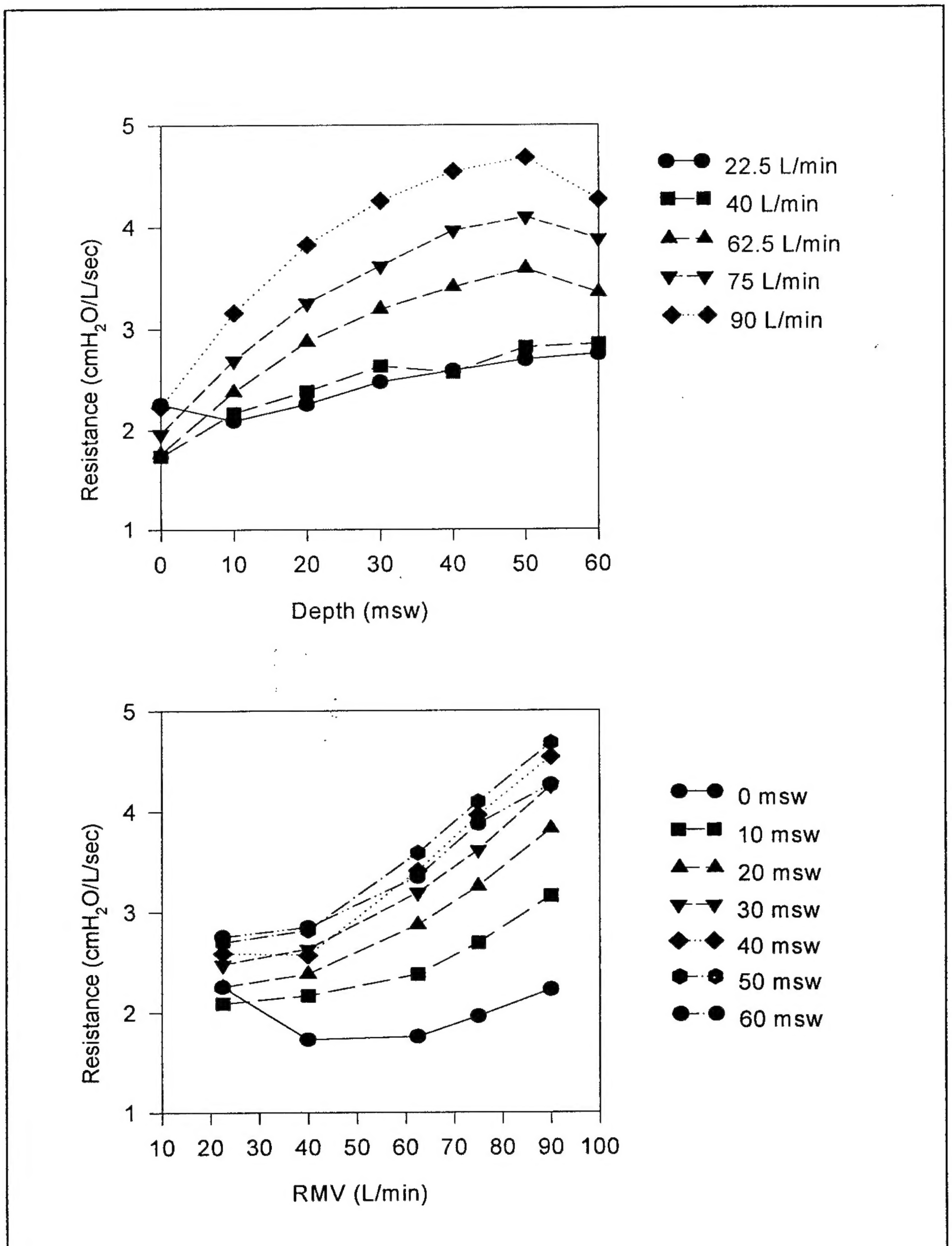

Figure 3. Resistance at 1500 psi supply pressure.

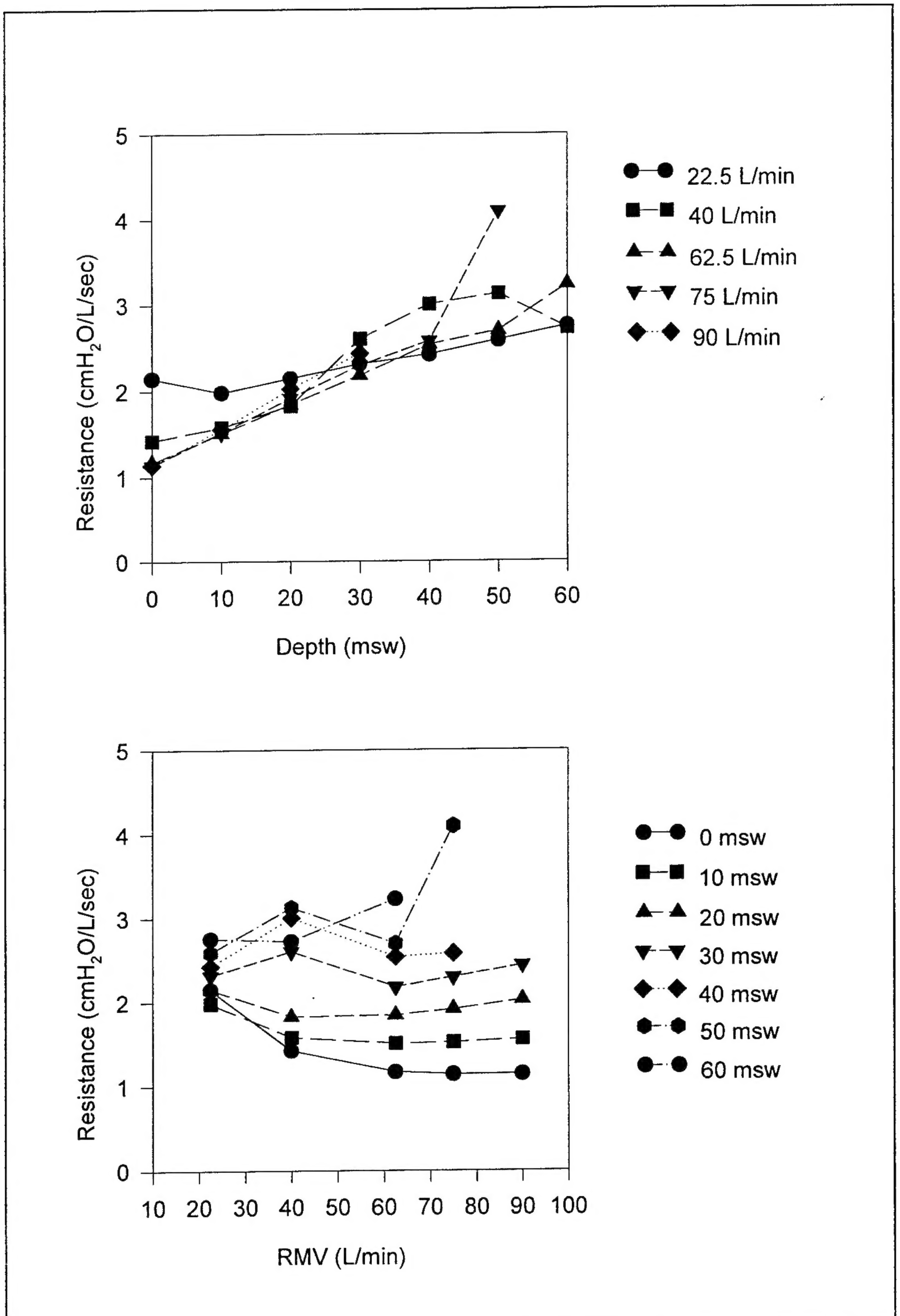

Figure 4. Resistance at 500 psi supply pressure.

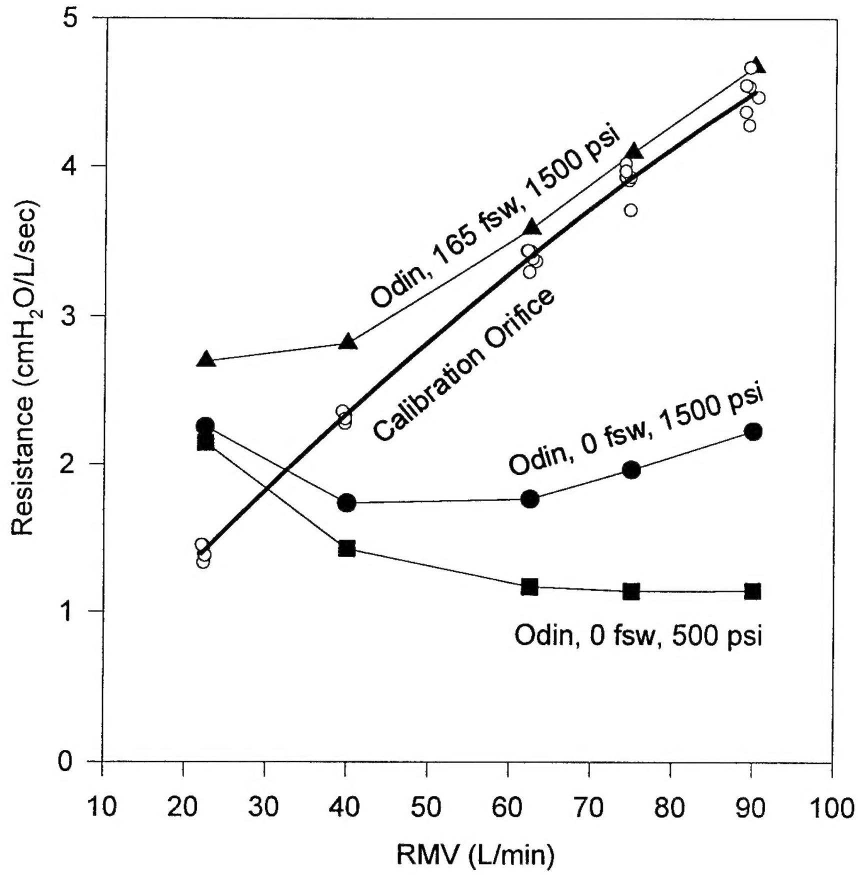

Figure 5. Comparison of Odin regulator and an orifice.